Dynamic Analysis of Nuclear Energy System Strategies for Electricity and Hydrogen Production in the USA

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Abstract – The role of nuclear energy in future sustainable energy parks gets an increasing focus in studies worldwide. Various roadmap exercises have been undertaken to look essentially to the technical solutions for nuclear energy to fulfill such a role. In parallel, studies are initiated addressing the possibilities for a hydrogen economy. Again, nuclear energy might play an important role in the production of vast amounts of hydrogen in an environmentally friendly and economic way. This paper reports on a preliminary dynamic analysis of the USA nuclear reactor park towards a more sustainable nuclear energy system with a combined production of electricity and hydrogen. The impact of the higher energy demand for additional hydrogen generation on the composition of the nuclear reactor park will be highlighted. It is shown that closure of the fuel cycle in such development scenarios has sustainability advantages for both resource efficiency and waste management. In addition, the additional cost for such advanced nuclear energy systems remains limited, i.e. 10% increase of cost of electricity and might make these nuclear energy systems acceptable in the future.

I. INTRODUCTION

Recognition of the role of nuclear energy for a sustainable energy generation is reflected in the USA by the recent activities initiated by the Department of Energy [1,2]. A key outcome of numerous related studies is the need for symbiotic nuclear energy systems [1]. Such symbiotic systems consist of different nuclear reactors each fulfilling a specific role to achieve two main objectives, i.e. match a growing energy demand and achieve sustainability. The latter objective includes resource efficiency, economics, safety, non-proliferation and waste management. The socio-political weighting of these different objectives changes over time and therefore requires flexibility in the development of such symbiotic nuclear energy systems. The fuel cycle is of paramount importance in achieving sustainability and different views on the kind of fuel cycle option have been expressed, ranging from continuation of the once-through fuel cycle to closure of the fuel cycle for transuranics (TRU) [1,2,3].

The transition from today's nuclear reactor park to such a symbiotic nuclear energy system involves a dynamic allocation of mass-flows in the nuclear fuel cycle, with an appropriate use of the fissile materials in different reactor types. Maximization of the economic value added and compliance with the sustainability objectives is key. The competitive electricity generation market has, so far, not stimulated the introduction of more innovative nuclear reactors and fuel cycle options to achieve the above objectives. The expected increase of fossil electricity generation costs in the future and especially the potential to open new markets for nuclear energy, i.e. hydrogen production, may create new opportunities in that respect. Viewed from a national energy policy perspective, the symbiosis in nuclear energy systems therefore seeks to maximize the economic value added for the system as a whole and for the individual reactors and fuel cycle plants by allocating the fissile materials to reactors according to their realizable contribution to this added value. This contribution may be either additional revenue generation or avoided present or future costs, e.g. closing the fuel cycle for reducing disposal costs or for adding to the longevity of affordable ore. Economics and non-proliferation considerations may limit the extent of closing the fuel cycle. The planning horizon over which economic added values is to be optimized should be at least as long as the economic value of the assets which is 40-60 years. Thus, governments play a specific and decisional role in shaping this symbiosis through incentives to optimize the system as a whole based on a long term planning horizon.

This paper addresses a systems dynamic analysis of the transition from today's nuclear reactor park to possible future symbiotic nuclear energy systems for the USA. The impact of the additional hydrogen demand on the development of such symbiotic systems will be highlighted. Composition of the nuclear reactor park, mass flows and overall expected economic performance are computed using a new code, DANESS, and the results are described. DANESS is an integrated nuclear process model for the analysis of today's and future nuclear energy systems on a fuel batch, reactor, and country, regional or even worldwide level [4].

II. NUCLEAR ENERGY SCENARIOS

The future of nuclear power will be substantially defined by the market. Where governments in the past actively guided the development of the energy production infrastructure, today, government's role has changed to a more indirect – but still very important – role of setting regulations for this market. The growing concern about climate change, energy security and economics currently influences the regulatory mechanisms for energy production towards a cleaner, more sustainable future. The current 104 nuclear reactors in the USA produce annually, on average, 770 TWhe at an average forward-going cost of 20.7 mills/kWhe [5,6]. This nuclear park avoids the emission of 164 million tons of CO_2 annually [7].

Nuclear energy is one of the few possible energy sources that mitigate emissions of greenhouse gasses (GHG) and is, today, the only technological viable solution to do this at massive scale. The growing interest in a hydrogen economy [8] has added possible new but important niches to the role of nuclear energy in the future [9]. However, waste management – and to a lesser degree safety and costs - are today the main impediments for a growing socio-political acceptance of nuclear energy. The growing energy demand worldwide, and especially the electricity component in it, might necessitate increased use of nuclear energy under the condition that nuclear may overcome these impediments.

This paper focuses on three of the main elements to solve these impediments, i.e. waste management, resource efficiency and economics. The paper will present the results of scenario analysis for potential nuclear energy development in the USA serving a growing energy and hydrogen demand. Four candidate nuclear energy system strategies have been analyzed in this respect. The scenarios are representative for some of the major choices one might take in developing nuclear energy systems serving a growing energy demand as is considered in the Gen-IV and AFCI programs [1,2]. All four were analyzed in a consistent way using the DANESS-code [4]. The scenarios are:

1. LWRs in once-through-cycle (OTC) mode as reference in business-as-usual scenario making electricity only.
2. LWRs + HTGRs in OTC-mode
3. LWRs + FRs with conversion ratio CR>1
4. LWRs + HTGRs + FRs (variable CR) with TRU-recycling

The (A)LWRs are considered to serve essentially the electricity market. In these scenarios, the HTGRs and FRs, due to their higher working temperature, are able to serve the hydrogen generation market using efficient hydrogen production processes (though they could make electricity, here they are assumed to make only hydrogen).

III. SCENARIO ASSUMPTIONS

Based on US/DOE EIA information as well as other projections of energy demand for the USA [9-11], a representative electricity and hydrogen demand scenario (regardless of source) was adopted for this study. This energy demand scenario assumes that electricity demand will grow by 1.9 %/yr during the period 2000-2020, and 1.4 %/yr thereafter. Within this overall growth, the nuclear energy demand for electricity generation is assumed to grow by 2%/yr after the year 2010. For hydrogen, the total demand for hydrogen in the US is expected to grow by 2.2 %/yr before the year 2020, and later on ranging from 1 to 1.6 %/yr depending on the sector of use[1]. In these scenarios, a growing part of this hydrogen demand, up to 25%, is assumed to be delivered through nuclear energy. Figure 1 shows the resulting assumed nuclear energy demand (expressed in equivalent electric energy demand) for these assumptions[2]. The figure also shows the effect of no or full relicensing of today's reactor park. Full relicensing means that all reactors would run for a full 60 years.

All nuclear energy system scenarios in this study were based on the figure 1 nuclear energy demand scenario[3]. While figure 1 only shows this energy demand until mid-century, all system scenarios were run until 2100 assuming the continuation of this energy demand scenario. Most of the results are truncated at the year 2050.

The attributes of the reactors and fuels used in this study are given in table 1. The PWR and BWR reactors refer to the current existing capacity based on DOE/EIA information [12]. ALWRs refer to future LWR deployments.

Front-end fuel cycle losses are assumed 0.1% where reprocessing recovery fractions are assumed 99.8% for all actinides.

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1 1 %/yr for transport, residential sector; 1.6%/yr for refinery; 1.4%/yr for commercial and 1.5%/yr for industrial sector.

2 Heat-to-electricity efficiency of 33% assumed for all reactors; heat-to-hydrogen efficiency of 50%.

3 The electricity demand in these scenarios differs from those used in the Gen-IV fuel cycle cross-cutting group [1] and recent MIT-report [3]. These scenarios result in a slower nuclear capacity growth.

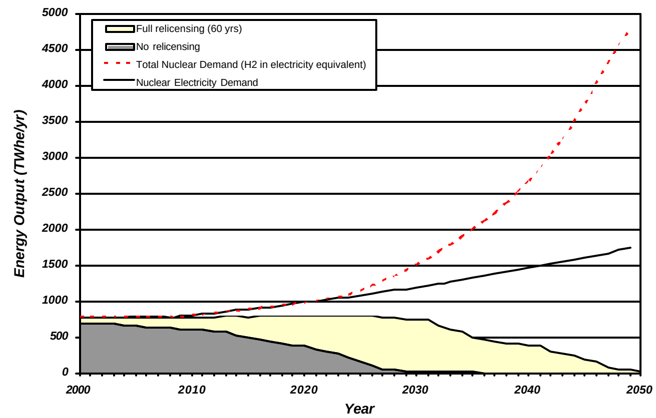

Figure 1. Energy Demand Scenario

Table 1. Reactor and fuel attributes (*: data averaged over core and blanket fuels)

Reactors	PWR	BWR	ALWR		HTGR	FR		
Thermal Power (MWth)	2647	2647	2647		600	843		
Electric Power (MWe)	900	900	900		284	320		
Thermal Efficiency (%)	34	34	34		47	38		
Capacity Factor (%)	90	90	90		90	85		
Technical lifetime (yr)	50	50	50		50	50		
						CR		
Fuels						0.25	0.5	1.25*
	UOX	UOX	UOX	MOX	Particle	Metal		
Average Burnup (GWd/tHM)	50	40	50	50	120	200	120	22
# fuel batches	5	5	5		3	7	7	3
Cycle length (mo)	12	12	12		12	12	12	12
Initial U (t/tIHM)	1	1	1	0	1	0	0	0
Initial enrichment (%)	4.2	3.7	4.2	0.25	15.5	0.25		
Initial DU (t/tIHM)	0	0	0	0.91903	0	0.0395	0.061	0
Initial REPU (t/tIHM)	0	0	0	0	0	0.3305	0.5936	0.9253
Initial Pu (t/tIHM)	0	0	0	0.08097	0	0.519	0.2919	0.0651
Initial MA (t/tIHM)	0	0	0	0	0	0.1117	0.0535	0.0009
Spent U (t/tIHM)	0.93545	0.94576	0.93545	0.88753	0.85917	0.3305	0.5936	0.8965
Spent enrichment (%)	0.82	0.8	0.82	0.15	4.8			
Spent Pu (t/tIHM)	0.012	0.1085	0.012	0.05512	0.01883	0.3769	0.2365	0.072
Spent MA (t/tIHM)	0.00125	0.00114	0.00125	0.0074	0.002	0.0897	0.0452	0.0077
Spent FP (t/tIHM)	0.0513	0.04225	0.0513	0.04996	0.12	0.2029	0.1248	0.0238

IV. BUSINESS-AS-USUAL SCENARIO

If only (A)LWRs in a once-through mode would be deployed to cover the electricity demand, the hydrogen component of demand in figure 1 would not be met. Even so, a total of 190 000 tHM spent fuel would be out-of-reactor by mid-century (i.e. more than 2.5 times the proposed capacity of Yucca Mountain). A total of 2 400 tHM transuranics (TRU), of which 2 180 tHM is plutonium (Pu), is contained in this SF, and this amount would be continuously growing as the nuclear park in a once-through mode operation would expand. Approximately 1.5 million tons natural uranium (U_{nat}) would have been used during the period 2000-2050 to fuel this (A)LWR reactor park of 220 GWe in 2050.

Assuming that the nuclear park worldwide experiences the same growth during these 50 years, a total of about 5.6 million tons of U_{nat} would have been consumed. Today, about 19 million tons of U_{nat} are expected to be available in the future, approximately 4 million tons being known and recoverable at <130 $/kg$U_{nat}$ cost [13]. Therefore, increased exploration to recover the other 14 million tons would have to be undertaken to fuel the world's nuclear reactor park in this scenario and would probably result in higher U_{nat} prices.

However, in case that (A)LWRs would generate all the projected hydrogen demand by electrolysis, a total of more than 250 000 tHM SF would have to be managed by mid-century (i.e. about 4 Yucca Mountains), where an additional 1 million tons of U_{nat} would be used.

The reference business-as-usual scenario based on a continuation of the once-through fuel cycle option would result in significant amounts of waste to be disposed of and would add additional pressure on the natural uranium price.

V (A)LWR + HTGR SCENARIOS

Responding to the assumed hydrogen energy demand by introduction of high temperature gas-cooled reactors (HTGR) operating in once-through mode may change this picture, especially for the back-end of the fuel cycle. Assuming that (A)LWRs would serve the electricity demand and HTGRs would be deployed for the hydrogen demand, an additional amount[4] of about 11 000 tHM SF from HTGRs would have to be managed by mid-century (on top of the 190 000 tHM from (A)LWRs). This amount is limited because of the high burn-up of HTGRs. The amount of TRUs out-of-reactor is shown in figure 2.

On the other hand, an additional 1.35 million tons of U_{nat} would be used to fuel these HTGRs because the high initial enrichment of 15.5% in ^{235}U for UOX fuel in HTGRs results in extensive use of U_{nat} and creation of a significant stock of depleted uranium (i.e. 3 million tons by mid century). The HTGRs do not add a significant burden to the amount of spent fuel to be managed and to be disposed, however, their impact on the front-end needs for U_{nat} and facilities (i.e. enrichment capacity) are very significant (see table 2).

Table 2. Front- and back-end Infrastructure Needs for Business-as-usual Scenario and (A)LWR+HTGR Scenario (in the year 2050).

	ALWR	ALWR + HTGR
Energy demand	Electricity	Electricity + hydrogen
U_{nat} used 2000-2050 (10^6 tHM)	1.5	2.85
DU stock (10^6 tHM)	1.95	3.05
Enrichment (tSWU/yr)	31 200	152 400
Fabrication		
UOX (tHM/yr)	5 150	5 150
HTGR (tHM/yr)	-	3 500
SF at-reactor storage (tHM)	20 100	27 200
SF Interim storage (tHM)	171 200	174 500

This (A)LWR+HTGR scenario can produce the hydrogen as well as electrical capacity growth and would result in a need of about three Yucca Mountain equivalent geological disposal sites to handle the spent fuel produced until mid-century. By the end of this century, at least 9 equivalent sites would be needed to handle the ALWR fuel alone without account being taken of the rapidly growing HTGR SF amount which is essentially defined by the evolution of hydrogen demand in the second half of this century.

[4] Compared to the business-as-usual case where (A)LWRs serve the electricity demand.

VI. (A)LWRS + FRS SCENARIOS

Closing the fuel cycle by reprocessing the spent fuel and recycling the transuranics (at least the Pu) in fast reactors has sustainability advantages for both resource efficiency and waste management and may be accomplished by a symbiotic use of (A)LWRs, HTGRs and fast reactors (FR).

The first question which arises is the total amount of energy that might be generated using only (A)LWRs and FRs, i.e. (A)LWRs essentially for electricity delivery (as in the previous business-as-usual scenario) and FRs for combined electricity and hydrogen generation due to their higher working temperatures. It's clear that only FRs with CR>1 are of any importance because CR<1 (burning) would result in lower FR capacity deployments and thus lower hydrogen generation capacity. A CR=1.25[5] case would contribute to both a better waste management and resource efficiency while maximizing the hydrogen production undertaken by more efficient high temperature processes.

In what follows, scenarios will also be presented for different reprocessing capacity deployment cases (rates of FR introduction) and different conversion ratios for the FRs, i.e. 0.25, 0.5 and 1.25.

Figure 3 shows the 'energy envelope' as may be generated by a (A)LWR (constrained to electricity demand) and FR CR=1.25 park. The (A)LWR fuel is assumed to be reprocessed by an aqueous process with a reasonable deployment scheme of 2 000 tHM/yr operational by the year 2020 and an additional 3000 tHM/yr by the year 2030. A five year cooling time at-reactor storage is included for UOX fuel. The metal FR fuel is reprocessed by dry techniques and also assumes a cooling time prior to reprocessing of 5 years. Today's PWRs and BWRs are assumed to have a 50 years lifetime and are shutdown by about 2045. Figure 3 clearly shows that faster FR introduction rates (through larger recycle facility deployment) or higher conversion ratios for FRs would be needed to deliver the energy demand for combined electricity and hydrogen generation with (A)LWRs and FRs alone.

The impact on the amount of spent fuel and transuranics out-of-reactor is shown in figure 4. The deployment of 5 000 tHM/yr aqueous reprocessing capacity for (A)LWR-UOX fuel would result in a cap on the amount of spent fuel and high level waste to be disposed of less than Yucca Mountain's licensed capacity at least until the middle of this century.

Figure 4 shows that in 2050 a total of 62 500 tHM UOX fuel and 8 500 tHM FR fuel would reside in the fuel cycle. The latter being essentially in at-reactor storage waiting for reprocessing. A 5 900 tHM HLW would have been produced from the accumulated losses in the reprocessing plants. The total amount of TRUs out-of-reactor amounts to some 1 950 tHM compared to the 2 400 tHM TRUs in the once-through case for (A)LWRs despite the higher amount of energy produced

[5] Only CRs up to 1.25 were assumed feasible in this study.

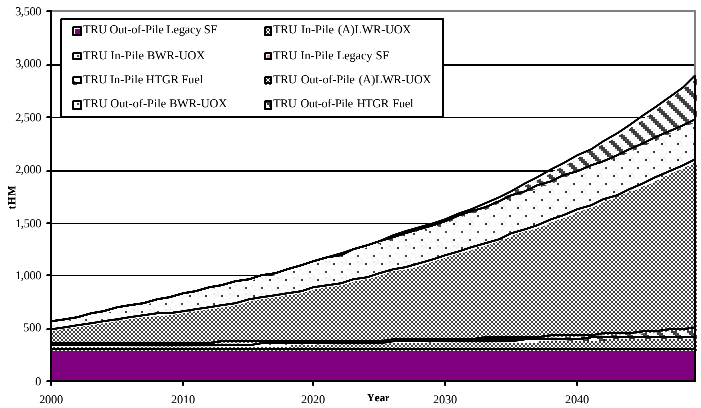

Figure 2. Amount of TRUs in-pile and out-of-pile for the (A)LWR + HTGR scenario.

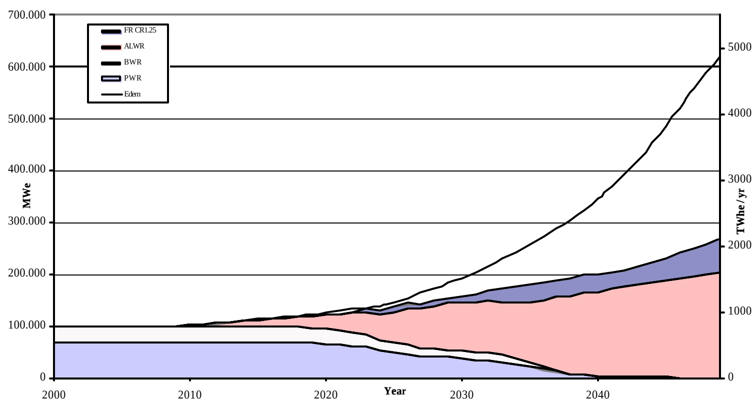

Figure 3. Energy Produced in A (A)LWR + FR (CR 1.25) Nuclear Energy System.

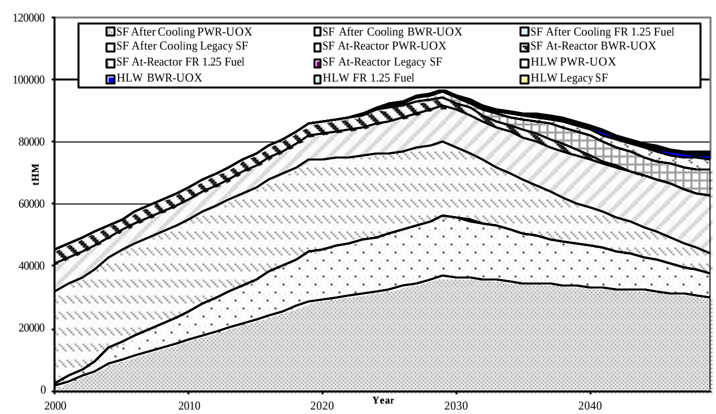

Figure 4. Total Amount of SF and HLW in Fuel Cycle for the Different Reactors.

the reactor park. In case an additional 3000 tHM/yr reprocessing plant for UOX-fuel would be deployed, the total SF amount in 2050 could be reduced to less than 21 000 tHM and about 8 000 tHM HLW.

The simulations until the end of century show that the total amount of SF and HLW to be disposed at each moment in time can be kept lower than the technical limit capacity of Yucca Mountain by installing about 9 000 tHM/yr reprocessing capacity for UOX fuel. The needed dry reprocessing capacity for these scenarios amounts to 1 200 tHM/yr in 2050.

VII. (A)LWR + HTGR + FR SCENARIOS

The previous scenarios showed that the assumed energy demand for electricity and hydrogen could not be fully matched by a (A)LWR and FR based reactor park with a reasonable deployment of reprocessing capacity sized to keep the amount of spent fuel in the fuel cycle constrained to Yucca Mountain's capacity. At least according the assumptions taken in these scenarios, a significant part of the reactor park should consist of HTGRs to provide for the remaining hydrogen generation demand. The FRs may be operated as TRU-burners to manage the fuel coming from (A)LWRs (HTGRs may be operated as Pu-burners as well in a once-through mode but that would result in an exacerbation of minor actinides in their spent fuel. We assumed in these scenarios that the TRU-burning occurs in FRs and HTGRs are operated in once-through mode).

Figure 5 shows the reactor park deployment for the scenario where (A)LWRs fulfil the electricity demand and where FRs and HTGRs fulfil the energy demand for hydrogen generation. The FRs are assumed to have a conversion ratio of 0.25. The aqueous reprocessing capacity has been assumed to be the same as before, i.e. 5 000 tHM/yr deployed by 2030. Figure 6 shows the corresponding amount of SF and HLW where only TRUs coming from (A)LWRs (including the initially existing LWRs) are burned in FRs and HTGRs operate in once-through mode.

For this scenario, the accumulation of SF and HLW is similar to the (A)LWR+FR scenario with an additional HTGR-fuel amount accumulating. The amount of TRUs in the fuel cycle amounts 1950 tHM by mid-century, 1 600 tHM being Pu contained in SF, HLW and in the front- and back-end fuel cycle facilities. A quite rapid growing part of this Pu is contained in SF from HTGRs.

The effect of a higher conversion ratio for the FR, i.e. CR=0.5 result in more FRs needed to burn the TRUs from (A)LWR and thus results in less HTGRs to be deployed and a somewhat slower build-up of SF, and Pu, in the SF from HTGRs. However, the effect is rather limited at this time-scale to mid-century.

Using a FR with breeding, i.e. CR = 1.25 as above, minimizes the amount of HTGRs (i.e. 290 GWe by 2050) needed for hydrogen generation. The resulting SF and HLW amounts in the fuel cycle are shown in figure 7. Figure 8 shows the corresponding amount of TRUs in the fuel cycle and in-pile (to be compared to figure 2 for the (A)LWR+HTGR scenario). As expected, the introduction of FRs results in a reduction of the amount of TRUs in the fuel cycle, i.e. out-of-pile, and this effect increases if the conversion ratio of the FRs is decreased. For the (A)LWR + HTGR + FR (CR 0.25) scenario, a total of 1820 tHM TRU in 2050 is accumulated to be compared to 2250 tHM for a CR 1.25 scenario and 2 400 tHM TRU s for the (A)LWR + HTGR scenario without FR deployment.

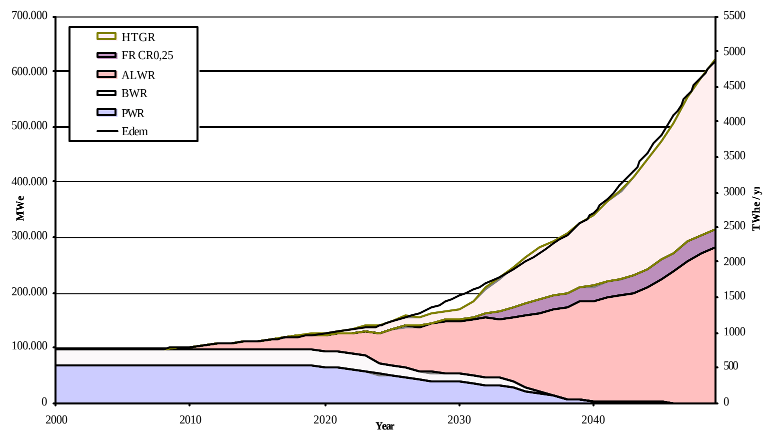

Figure 5. Reactor park composition for a (A)LWR+HTGR+FR (CR=0.25) scenario.

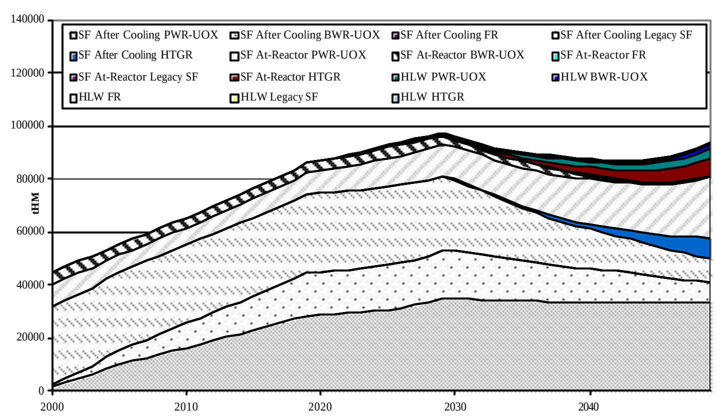

Figure 6. Amount of SF and HLW for a (A)LWR+HTGR+FR (CR 0.25) scenario.

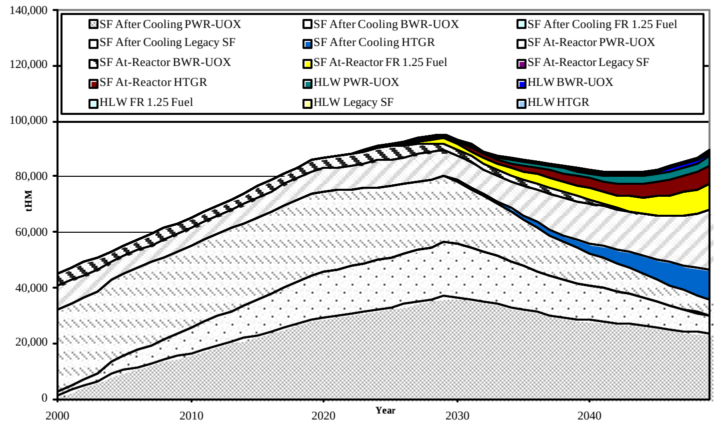

Figure 7. Amount of SF and HLW for a (A)LWR+HTGR+FR (CR 1.25) scenario.

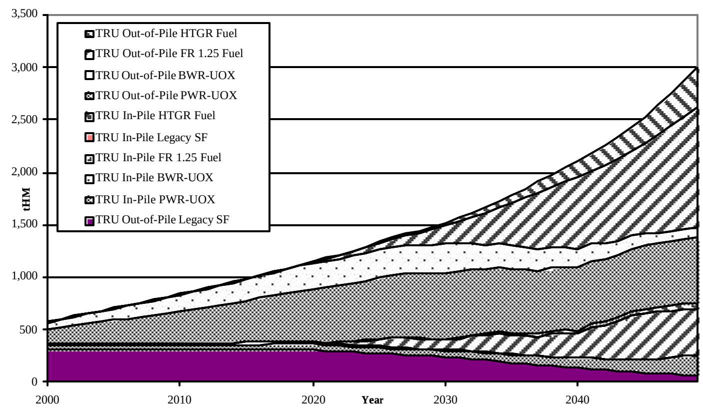

Figure 8. Amount of TRUs in-pile and out-of-pile for the (A)LWR+HTGR+FR (CR 1.25) scenario.

VIII. ECONOMICS

Based on economic data collected by ANL on reactor and fuel cycle facility costs, table 3 summarizes the energy park average cost of energy production (in constant money terms) for the three nuclear reactor parks in the above nuclear energy system scenarios. The first column is for a park producing electricity. The second is for a once-though (A)LWR+HTGR park providing electricity and hydrogen. The third column corresponds to a combined electricity and hydrogen producing park with closure of the fuel cycle. In the development of these costs, the operation and maintenance costs for the three reactor types used in these scenarios, i.e. (A)LWR, HTGR and FR where all set at 15 \$/MWhe. Capital costs were calculated as 25.6, 20.5 and 37.7 \$/MWhe respectively. The capital costs contributing to energy cost were calculated assuming the economic lifetime for the reactors being 17 years, i.e. one third of their technical lifetime (50 years) and an average cost of capital of 12 % was assumed for all reactors. Fuel costs for (A)LWRs in once-through mode amounted to 9.2 \$/MWhe and 9.9 \$/MWhe for HTGRs. The fuel cost for FRs were calculated as 49.5 \$/MWhe.

Table 3. Average Energy Park Generation Costs for Different Nuclear Energy System Scenarios.

\$/MWhe	(A)LWR	(A)LWR + HTGR	(A)LWR + HTGR + FR CR 1.25
	Electricity	Electricity + hydrogen	Electricity + hydrogen
2020	50.1	49.9	55.3
2050	49.9	46.9	55.8

The capital costs for FRs are based on a 2 000 \$/KWe overnight cost, compared to 1500 for (A)LWRs and 1 150 for HTGRs. Fuel costs for HTGRs account for the higher enrichment needs compared to UOX-fuel and the assumed fabrication cost of 700 \$/kgHM for particulate fuel. Fuel costs for FRs include dry reprocessing and fabrication costs for all the FR-fuel (i.e. including driver and blanket fuel) at an average cost of 1 100 and 1 500 \$/kgHM respectively.

The energy park average cost is given for the years 2020 and 2050 in table 3. It shows the limited increase in cost of energy production in the new hydrogen market and in a closed fuel cycle which caps waste production. It should be mentioned that no account has been taken in this analysis for any potential cost reduction due to reduced TRU-disposal in repository.

Nonetheless, table 3 also shows that the average cost of energy generation by such a symbiotic nuclear reactor park which puts a cap on waste generation remains relatively unaffected by the move to hydrogen production and the introduction of TRU-burning in FRs. The energy cost increase for the whole system compared to a business-as-usual once-through fuel cycle operation remains within about 10%.

IX. CONCLUSIONS

This paper analyzed the impact of alternative symbiotic nuclear energy systems deployment paths for a mixed electricity and hydrogen energy demand scenario. It was shown that a symbiotic nuclear reactor park consisting of (A)LWRs, HTGRs and FRs would be capable to maintain a growing electricity market share while entering the market for hydrogen generation and at the same time avoiding the construction of additional waste repositories. The closure of the fuel cycle for TRUs might be further improved if reprocessing of HTGR-fuels would be considered as well for recycling of the TRUs in FRs.

Given the entry of nuclear into the hydrogen sector of the energy market, the impact of recycle on the management of the back-end of the fuel cycle is important to cap growth of the waste burden and would lead to improved waste management schemes at a cost increase of 10% compared to the once-through fuel cycle option.

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